5G New Radio in mmWave Spectrum Bands

June 2nd , 2017

Summary

- **Nokia is fully committed to 5G @ bands below 52.6GHz (3GPP Phase 1)**

- **Nokia also sees value in 5G @ 70/80 GHz (part of 3GPP Phase 2)**
  - 10 GHz of spectrum available worldwide and under study in ITU
  - Use 2 GHz of BW can meet 3GPP requirements
    - > 10 Gbps Peak Rate
    - > 100 Mbps of cell edge rate

- **Higher mmWave Spectrum is no different than lower mmWave spectrum:**
  - Similar channel models
  - Higher pathloss can be mitigated by using large number of antenna elements
  - Marginal performance difference between high and low mmWave bands
  - Many similarities in RFIC technology between higher and lower mmWave bands

- **Feasibility**:
  - Nokia has demonstrated 70 GHz PoC with multiple features
  - Nokia has addressed co-existence issues with existing backhaul links

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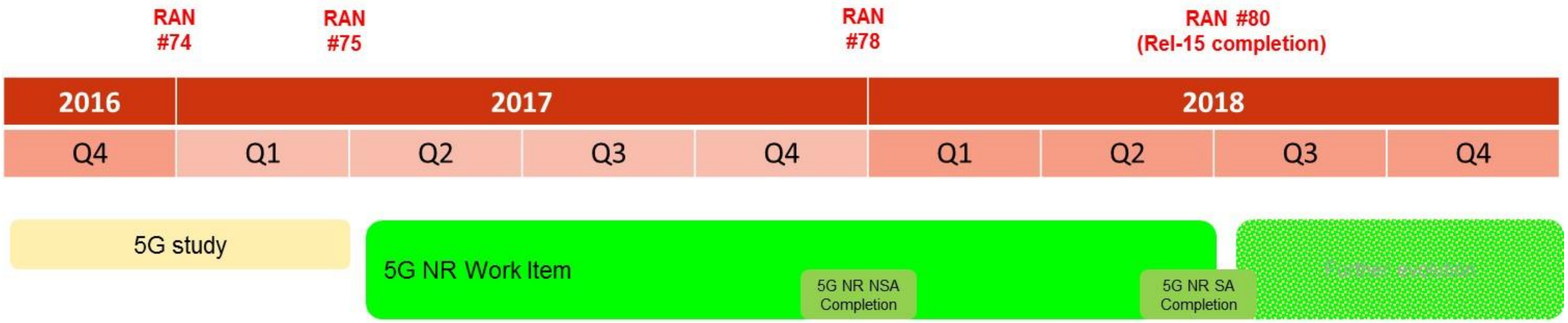
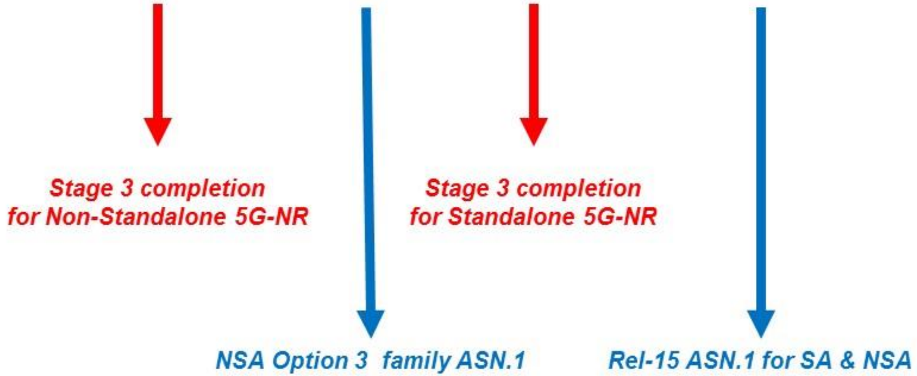
5G New Radio- 3GPP Timeline

3GPP Agreed Release 15 WI 5G timeline

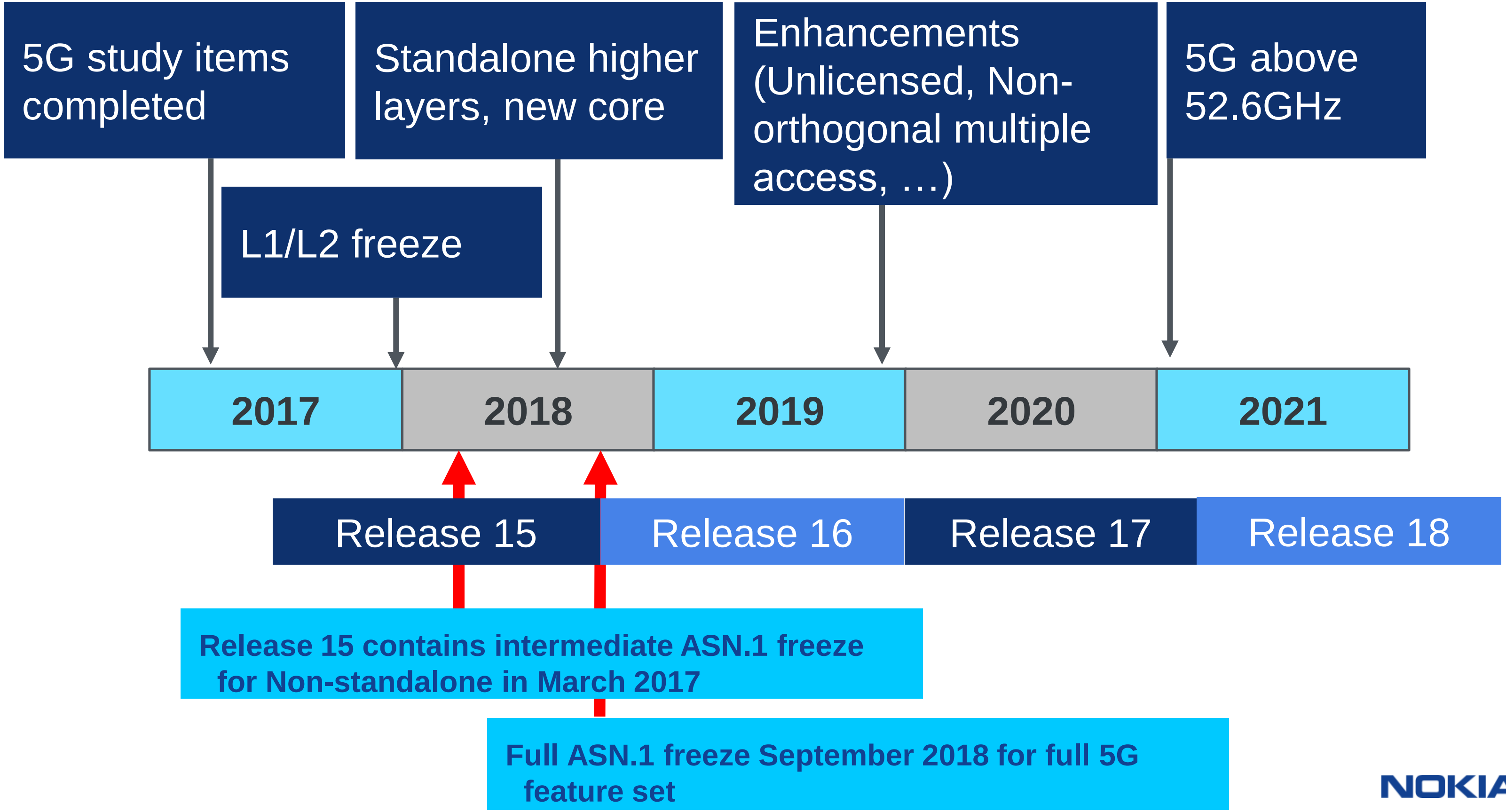


Single set of specs, including single Radio Resource Control specification



NSA = Non StandAlone = EPC core ("Option 3") & LTE anchor
SA = StandAlone

5G (New Radio) Schedule in 3GPP (Release 16/17 schedule TBC)



Summary of 5G RAN prioritization

Phase 1 WI (Rel-15)
- Main assumption: general support for stand-alone NR below 40GHz (option 2 scenario) including DC
- 4G-5G interworking
- MIMO/Beamforming (fundamental features)
- Mini-slot (note: enabler for URLLC and ensures forward compatibility)
- Public warning/emergency alert (for regulatory needs)
- SON functionality for Dual Connectivity
- RRC inactive data

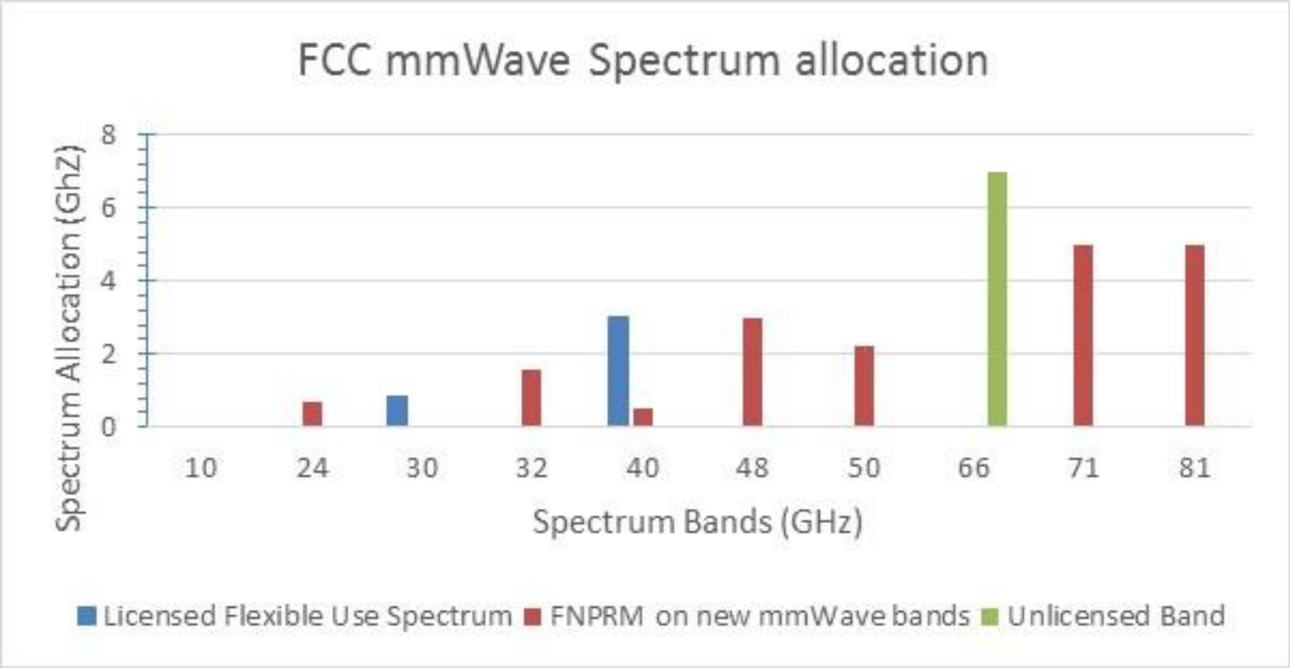
Phase 2 WI (Rel-16)
- Potential enhancements for eMBB support below 40GHz
- URLLC (below 40GHz)
- 4G-5G interworking – remaining options
- Shared spectrum and 5GHz unlicensed spectrum
- Location/positioning functionality (for regulatory needs)
- MIMO enhancements

Note: some Phase 1 SIs might belong to Phase 2 WI as well (not shown here explicitly)

Phase 1 SI (Rel-15)
- **Unlicensed spectrum**
- **URLLC (below 40GHz)**
- **Non-orthogonal multiple access**
- Location/positioning functionality (for regulatory needs)
    - Indoor/Outdoor
- New SON functionality
- Sidelink (use cases out of reach of LTE evolution)
- NR-Wi-Fi interworking
- **Integrated Access Backhaul**
- **Non-terrestrial networks**
- **eV2V evaluation methodology**

Phase 2 SI (Rel-16)
- mMTC
- **Waveforms for >40GHz**
- **URLLC for >40GHz**
- **MIMO for >40GHz**
- Multi-connectivity (for >2 nodes)
- Uplink based mobility
- 2-step RACH
- TX interference coordination
- **V2V and V2X (use cases out of reach of LTE evolution)**
- **NAICS**
- Multimedia Broadcast/Multicast Service
- **Air-to-ground and light air craft communications**
- Extreme long distance coverage
- Satellite communication
- Other verticals
- **60GHz unlicensed spectrum**

FCC mmWave Spectrum Allocation



5G New Radio- mmWave Challenges and Peak Rates

5G mmWave Challenges & Proof Points

- **Unique difficulties that a mmWave system must overcome**
  - Increase path loss which is overcome by large arrays (e.g., 4x4 or 8x8)
  - Narrow beamwidths, provided by these high dimension arrays
  - High penetration loss and diminished diffraction

- **Two of the main difficulties are:**
  - Acquiring and tracking user devices within the coverage area of base station using a narrow beam antenna
  - Mitigating shadowing with base station diversity and rapidly rerouting around obstacles when user device is shadowed by an opaque obstacle in its path

- **Other 5G aspects a mmWave system will need to address**:
  - High peak rates and cell edge rates (>10 Gbps peak, >100 Mbps cell edge)
  - Low-latency (< 1ms)

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5G Peak Rates

- 4G achieved 10-15% of the target bit rate in the first deployment and the full target four years later.
- Extrapolating to 5G would give 5 Gbps by 2020 and 50 Gbps by 2024

	Target bit rate	3GPP specs	1st deployment	Wide-scale Adoption
4G = LTE-Advanced	1 Gbps	2011 3GPP Release 10	2013 150 Mbps	2017 1 Gbps
5G	50 Gbps	2018 3GPP Release 14	2020 5 Gbps	2024 50 Gbps

5G mmWave : Channel Models

UMi Large-scale Propagation Model : Path loss / Shadow Fading (Example)

- Pathloss model based on multiple measurement campaigns
  - LoS model – well matched to Friis' free-space path loss model
  - NLoS model – path loss slope range (n/α ≈ 3~4) similar to lower-band, below 6 GHz
- Pathloss difference between higher and lower frequencies can be compensated by using larger number of antenna elements

Single-slope Baseline Path loss Model (LoS / NLoS)

Closed-in Ref-d0 (CI) Model : $\boldsymbol{PL}(d)[dB] = 10\,\boldsymbol{n}\mathbf{log_{10}}(d\,[m]/\boldsymbol{d_0}) + \mathbf{32.45} + \mathbf{20log_{10}}(f_c\,[GHz]) + \boldsymbol{\chi_\sigma}(d)$ ($\boldsymbol{d_0}$=1m)

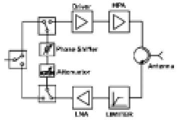
α-β-γ Mode : $\boldsymbol{PL}(d)[dB] = 10\,\boldsymbol{\alpha}\,\mathbf{log_{10}}(d\,[m]) + \boldsymbol{\beta} + 10\,\boldsymbol{\gamma}\,\mathbf{log_{10}}(f_c\,[GHz]) + \boldsymbol{\chi_\sigma}(d)$

Single-Slope Path loss Model			Baseline Model : CI model (LoS), CI / α-β-γ model (NLoS)				Valid freq. [GHz]	Validity dist. [m]
			n (CI) / α	β [dB]	γ	σ_{SF} [dB]	[min ~ max]	[min ~ max]
Street Canyon	LoS		2.1	N/A	N/A	3.76	2 ~ 73	5~221
	NLoS	CI	3.17	N/A	N/A	8.09		10~959
		ABG	3.53	22.4	2.13	7.82		
Open Square	LoS		1.85	N/A	N/A	4.2	2 ~ 60	6~88
	NLoS	CI	2.89	N/A	N/A	7.1		8~605
		ABG	4.14	3.66	2.43	7.0		

Phased Array Technology

Basic technologies vs. band of operation

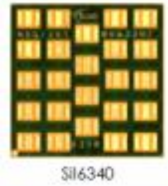
		3.5 GHz	15 GHz	28 GHz	38 GHz	60 GHz	73 GHz	83 GHz	94 GHz
Wavelength	mm	86	20	11	7.9	5.0	4.1	3.6	3.2
Row/column	#	8	8	8	8	8	8	8	8
Total	#	64	64	64	64	64	64	64	64
Width/Height	mm	342.9	80.0	42.9	31.6	20.0	16.4	14.5	12.8
Technology		T/R Module using Mech array assembly	Monolithic T/R Modules on Interposer	T/R Modules or MMIC on Interposer	T/R Modules or MMIC on Interposer	1 or more MMIC on Interposer board	Multiple MMICs , chip-scale antenna or interposer	Multiple MMICs , chip-scale antenna or interposer	Multiple MMICs using chip scale antenna



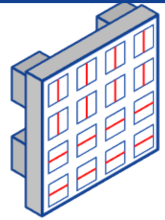
PA, LNA, phase shifter, VGA and T/R diplexing mechanically assemble into phased array. MMIC solutions preferred

Migrate to MMIC as frequency increases to reduce cost and improve manufacture

Transition region where either scalable MMIC or T/R module approach may be viable



Silicon Image 60GHz MMIC on LTCC interposer board with antenna array



Transition region for interposer board vs. wafer-scale antennas

Circuits same size as antenna array.(UCSD 94GHz Chip Scale Ant array)

* MMIC = Monolithic Microwave Integrated Circuit

Device Technology for 28/39 GHz vs. 71/81 GHz

Many Similarities

All are high frequency bands with small wavelengths

- All need highly integrated, MMIC based arrays of antennas to increase aperture size

Modern SiGe and CMOS semiconductors are fast and getting faster

- They provide sufficiently fast transistors for usable gain in all these bands
- E-Band devices can have slightly lower gain and higher NF and phase noise than in K/Ka band devices, their performance is remains acceptable

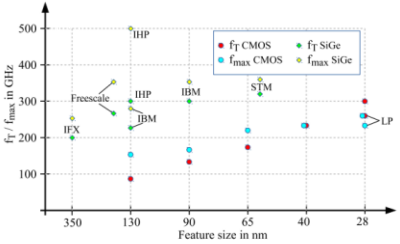


Fig. 2. Measured speed of CMOS and SiGe transistors

Packaging losses are manageable in all bands

- Higher loss at higher frequency (due to more wavelengths in the same material) is offset by smaller antenna element spacing and thus shorter distances from die to antenna
- Lower frequencies may benefit from hybrid semiconductor solutions and have an easier path to dual-polarized arrays
- While higher frequencies offer opportunities for highly integrated large scale arrays and low cost wafer-scale antenna fabrication

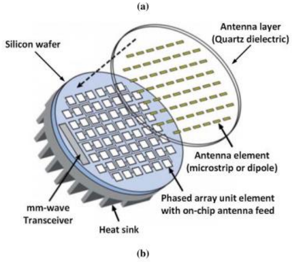


Fig. 1. (a) Phased array based on a small silicon chip on an interposer and multilayer PCB. (b) Wafer-scale phased array.

[1] "Driving Towards 2020: Automotive Radar Technology Trends", J. Hasch, 2015 IEEE MTT-S International Conference on Microwaves for Intelligent Mobility
[2] "60-GHz 64- and 256-Elements Wafer-Scale Phased-Array Transmitters Using Full-Reticle and Subreticle Stitching Techniques", G. Rebeiz, et. Al., IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, DEC 2016

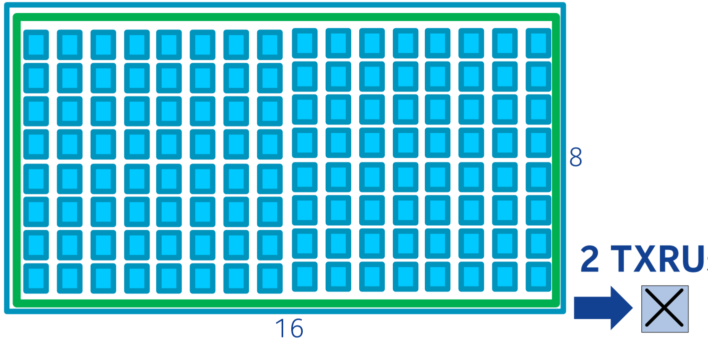
System Level Simulation Results

Antenna Array Comparisons - Number of Elements Constant vs. Frequency

5dBi ant element gain, 7dBm AP Pout per element, 1dBm UE Pout per element, shown to scale

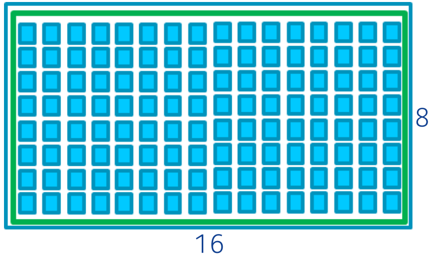
AP

28 GHz
256 elements (8x16x2)



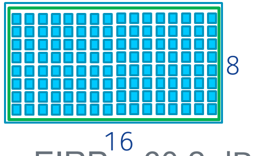
Max EIRP ≈ 60.2 dBm

39 GHz
256 elements (8x16x2)



Max EIRP ≈ 60.2 dBm
52% area relative to 28GHz

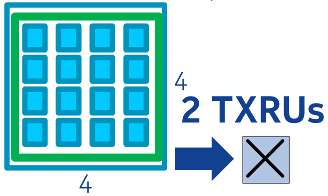
73 GHz
256 elements (8x16x2)



Max EIRP ≈ 60.2 dBm
15% area relative to 28GHz

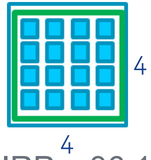
UE

28 GHz, 32 elements, (4x4x2)



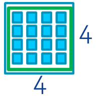
Max EIRP ≈ 36.1 dBm

39 GHz, 32 elements, (4x4x2)



Max EIRP ≈ 36.1 dBm
52% area relative to 28GHz

73 GHz, 32 elements, (4x4x2)



Max EIRP ≈ 36.1 dBm
15% area relative to 28GHz

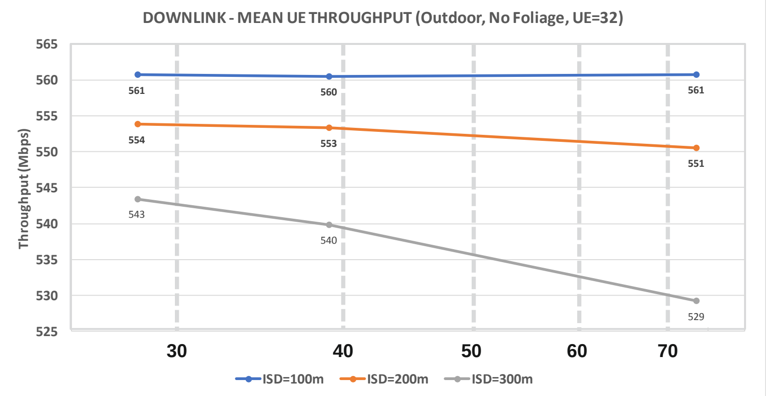
System Simulation Results for the Suburban Micro Environment

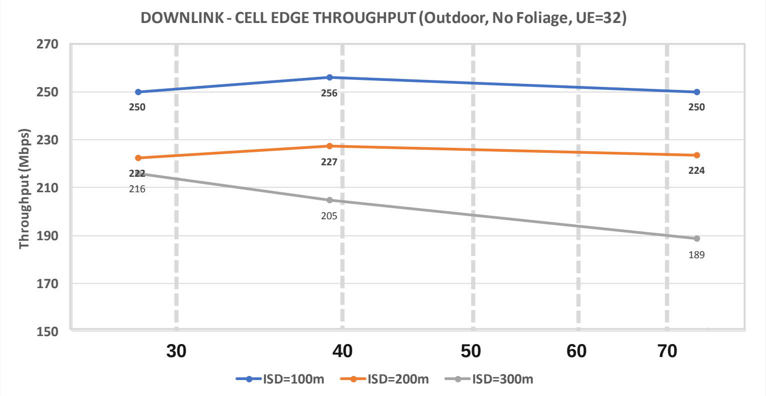
Constant Number Antenna Elements for 28 GHz, 39 GHz and 73 GHz

Mean UE Throughput

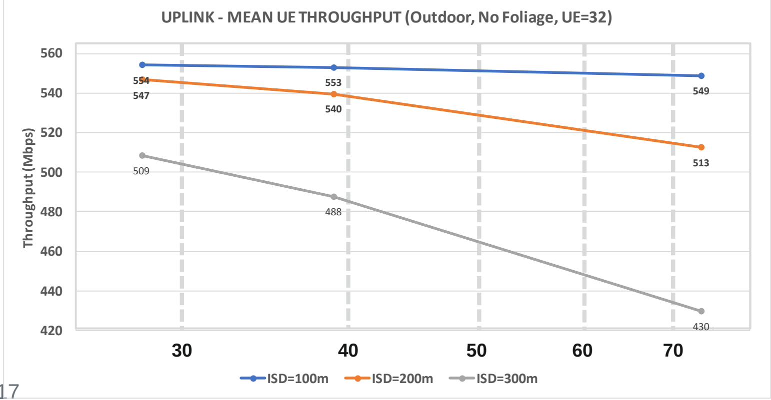
Cell Edge Throughput

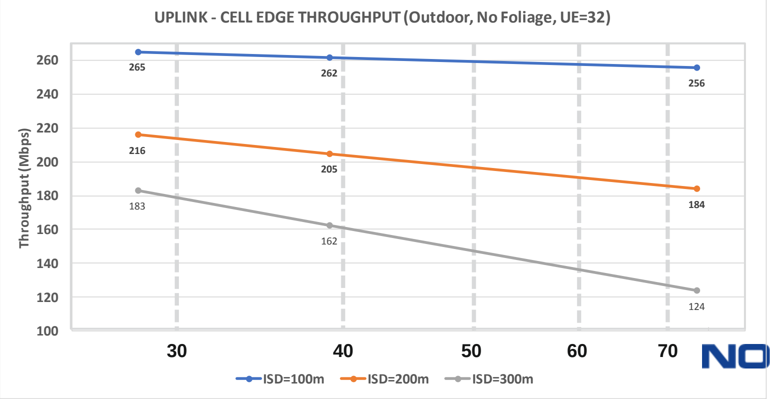
Downlink





Uplink





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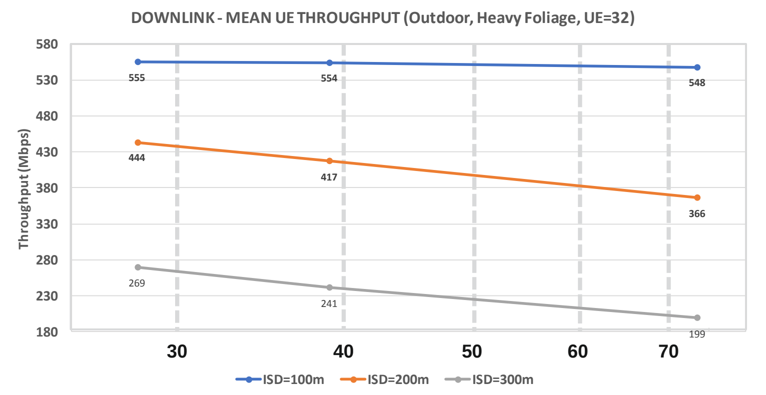
System Simulation Results for the Suburban Micro Environment (Heavy Foliage)

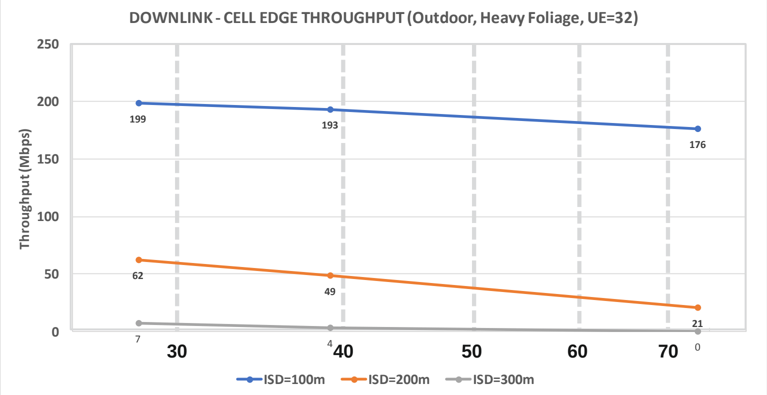
Constant Number Antenna Elements for 28 GHz, 39 GHz and 73 GHz

Mean UE Throughput

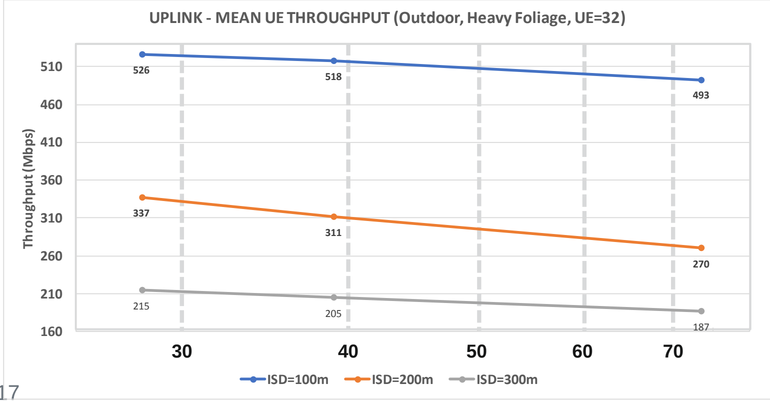
Cell Edge Throughput

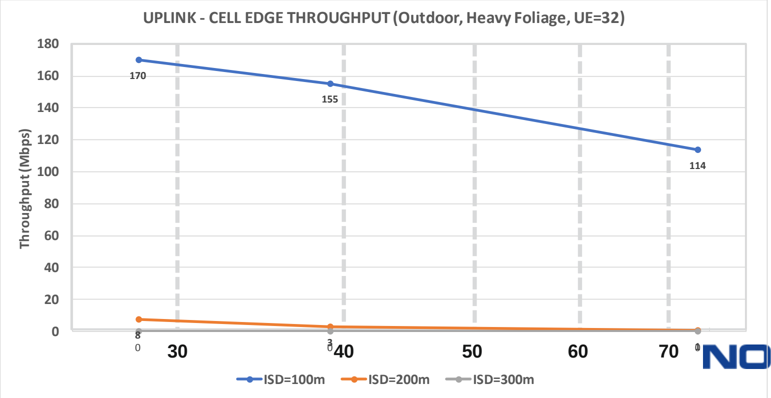
Downlink





Uplink



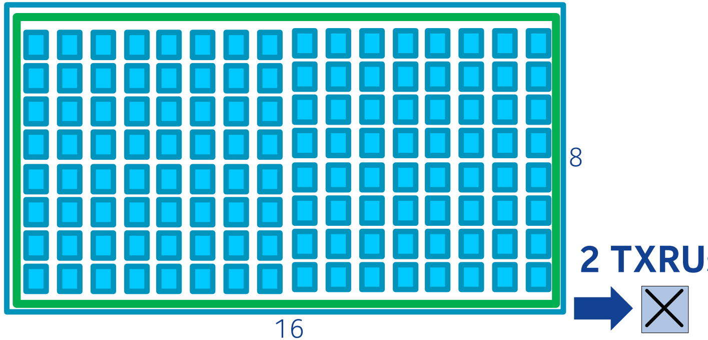


Antenna Array Comparisons - AP Antenna Aperture Constant vs. Frequency

5dBi ant element gain, 7dBm AP Pout per element, 1dBm UE Pout per element, shown to scale

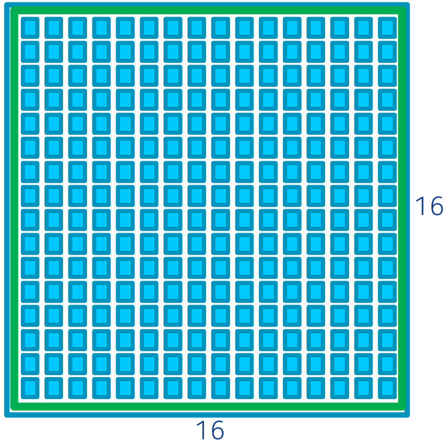
AP

28 GHz
256 elements (8x16x2)



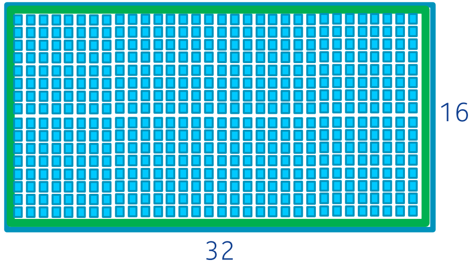
Max EIRP ≈ 60.2 dBm

39 GHz
512 elements (16x16x2)



Max EIRP ≈ 66.2 dBm
103% area relative to 28GHz

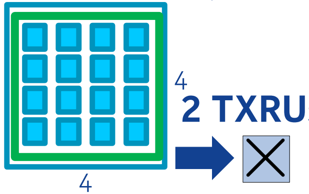
73 GHz
1024 elements (16x32x2)



Max EIRP ≈ 72.2 dBm
59% area relative to 28GHz
Room to grow…normalized array size is ~4.5dBm more than above

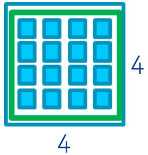
UE

28 GHz, 32 elements, (4x4x2)



Max EIRP ≈ 36.1 dBm

39 GHz, 32 elements, (4x4x2)



Max EIRP ≈ 36.1 dBm
52% area relative to 28GHz

73 GHz, 32 elements, (4x4x2)

Max EIRP ≈ 36.1 dBm
15% area relative to 28GHz

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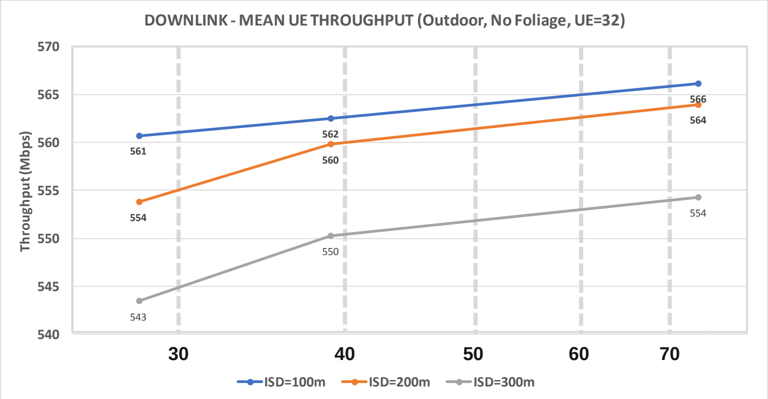
System Simulation Results for the Suburban Micro Environment

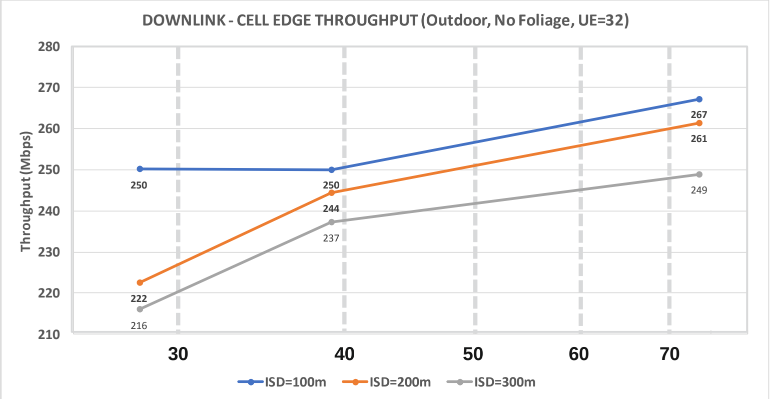
Constant Antenna Aperture for 28 GHz, 39 GHz and 73 GHz

Mean UE Throughput

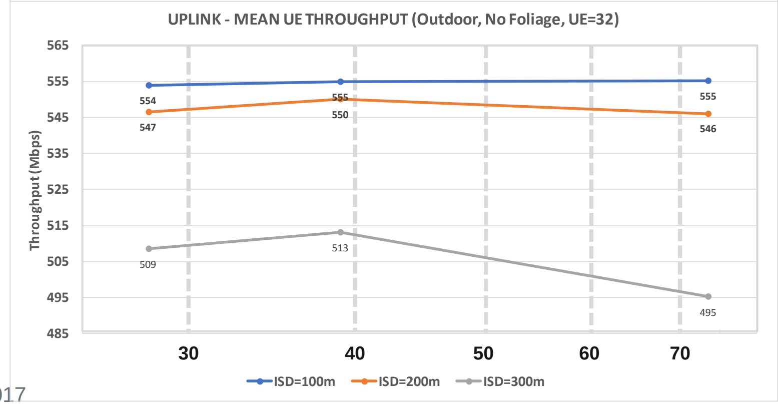
Cell Edge Throughput

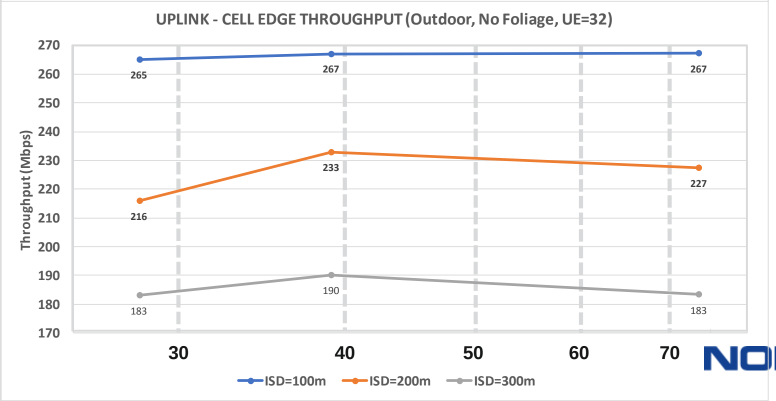
Downlink





Uplink





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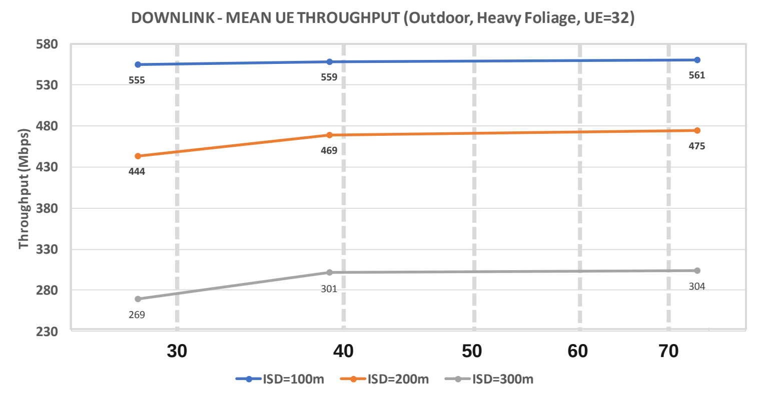
System Simulation Results for the Suburban Micro Environment (Heavy Foliage)

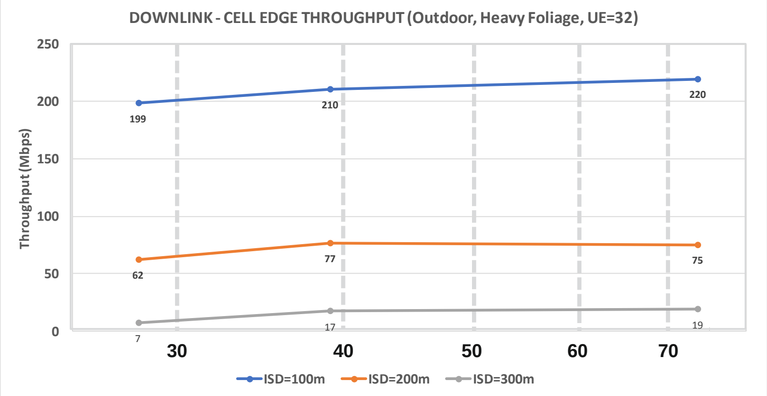
Constant Antenna Aperture for 28 GHz, 39 GHz and 73 GHz

Mean UE Throughput

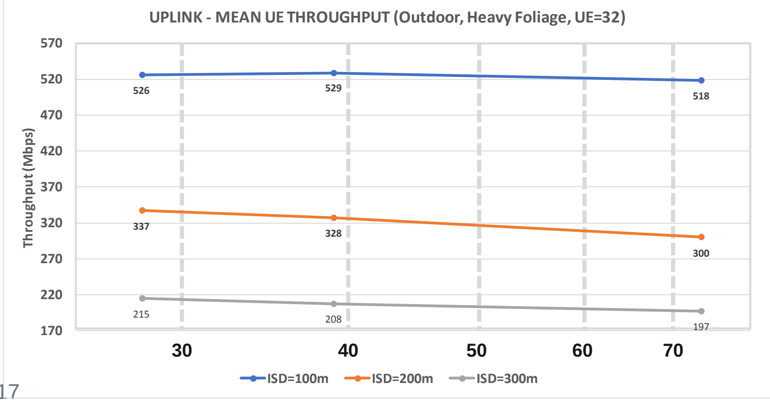
Cell Edge Throughput

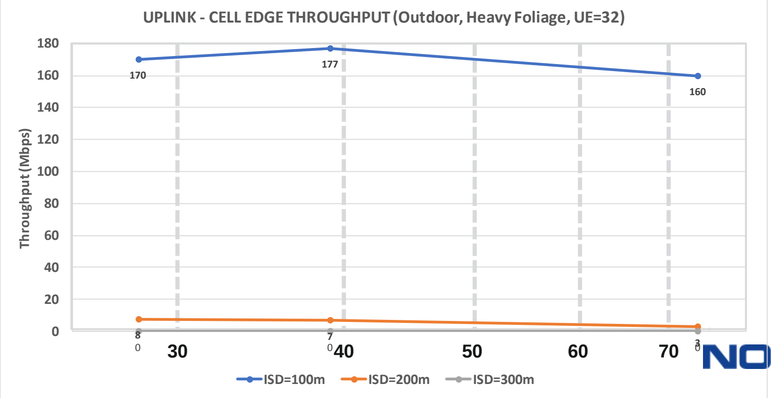
Downlink





Uplink





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System Simulation Results
Summary

- Antenna array size will decrease for given array configuration and number of elements
  - Reduced antenna aperture is the primary reason for decreasing performance with higher frequency
  - Little degradation is seen at 100m ISDs as systems are not path loss limited
  - Some degradation is seen for larger ISDs as systems become more noise limited
- Keeping antenna aperture constant can mitigate differences at higher frequencies
  - Increasing the number elements as frequency increases will keep the physical array size and antenna aperture constant
  - Performance is nearly identical at all frequencies and ISDs with constant physical array size (antenna aperture)
  - Slight improvements in downlink performance if power per element is held constant as number of elements is increased
- Foliage poses challenges at all mmWave frequencies and is not dramatically higher at 70 GHz as compared to 28 GHz or 39 GHz

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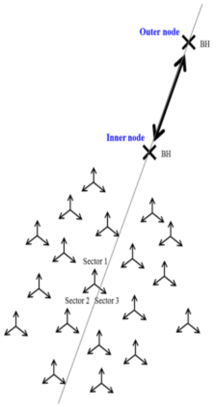
Co-existence of Access and Backhaul

Fixed Service Backhaul-5G Coexistence at 70/80 GHz

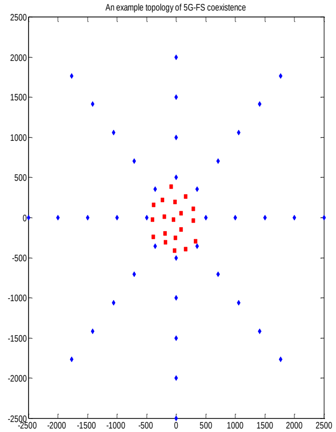
- Existing terrestrial licensees have used the spectrum band solely for fixed services, including backhaul

- Coexistence of 5G with Fixed Links was studied.

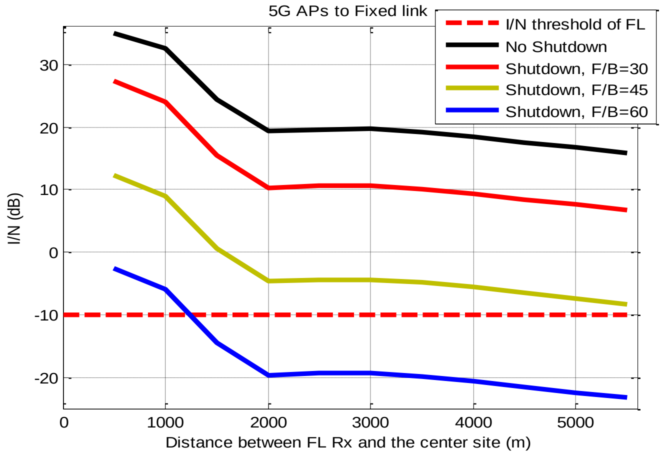
- Effective Mitigation Techniques like shutting down the 5G AP beam(s) responsible for interference at the fixed node were investigated.



Orientation of Fixed link and 5G sectors



Fixed links surrounding 5G



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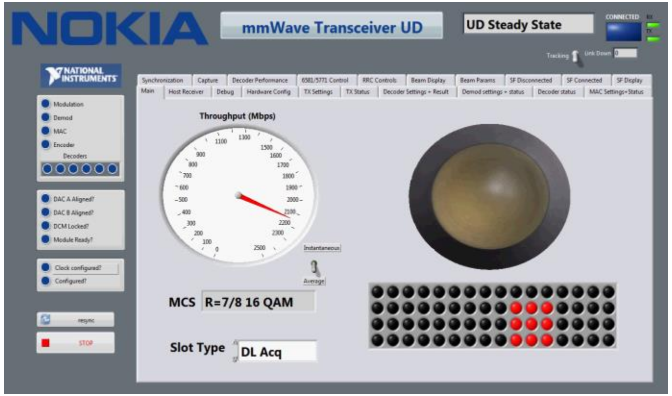
Nokia’s PoC @ 70 GHz

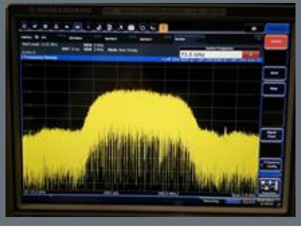
Nokia 5G mmWave beam tracking demonstrator (70 GHz)

First 5G demos
CEATEC 2014

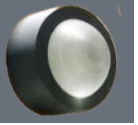


- 70 GHz PoC System
  - 1 GHz BW (2.5 Gbps Peak Rate)
  - 2 GHz BW (2x2 MIMO, 15 Gbps Peak Rate)

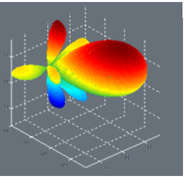
70 GHz band
1 GHz bandwidth



Lens antenna with 64-beam switching



3˚ beam width



Summary: Why 5G @ 70 and 80 GHz Band

- **10 GHz of Spectrum available worldwide and under study in ITU**
  - Use 2 GHz of BW can meet 3GPP requirements
    - > 10 Gbps Peak Rate
    - > 100 Mbps of cell edge rate

- **Higher mmWave Spectrum is no different than lower mmWave spectrum:**
  - Similar channel models
  - Higher pathloss can be mitigated by using large number of antenna elements
  - Marginal performance difference between high and low mmWave bands
  - Many similarities in RFIC technology between higher and lower mmWave bands

- **Feasibility**:
  - Nokia has demonstrated 70 GHz PoC with multiple features
  - Nokia has addressed co-existence issues with existing backhaul links

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